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Petrographic and Core Analysis of the Jurassic Norphlet Formation: A Case Study in the Lithofacies Control of Diagenesis and Porosity in the Flomaton Field, AL

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**Petrographic and Core Analysis of the Jurassic Norphlet Formation: A Case Study in the
Lithofacies Control of Diagenesis and Porosity in the Flomaton Field, AL**

Jarrett Smith

**Thesis submitted
to the Eberly College of Arts and Sciences
at West Virginia University**

**in partial fulfillment of the requirements for the degree of
Master of Science
in Geology**

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Abstract

Petrographic and Core Analysis of the Jurassic Norphlet Formation: A Case Study in Facies Control of Diagenesis in the Flomaton Field, AL

Jarrett Smith

This study includes a sedimentologic and petrographic study of cores and thin-sections from the Jurassic Norphlet Formation in the Flomaton Field in southern Alabama to define a specific paragenetic history of each facies encountered and to identify key controls on reservoir quality. Eolian dune, nearshore, sand flat, and wadi facies were likely encountered in Norphlet core and thin-section samples that displayed a high degree of heterogeneity between them in terms of porosity, grain contacts, cement abundance/type, intergranular volume, and overall diagenetic processes. These distinct petrographic differences suggest that the paragenesis in the Flomaton Field is primarily facies controlled. The eolian dune facies, which serves as a significant oil and gas reservoir in the Norphlet Formation, exhibits a mean porosity of 16% despite being buried to depths exceeding 16,000 feet in southern Alabama. This preservation of porosity likely resulted from an introduction of a halite cement, prior to compaction, that tended to keep the grains apart during eogenesis, but was later removed due to dissolution resulting from migrating fluids associated with hydrocarbon charging of the Norphlet reservoir.

Authigenic clay coats are present in the eolian dune and sand flat facies but they are not suggested to be the primary factor in porosity preservation as they were in the Norphlet Formation of Mobile Bay. In the up-dip Flomaton Field, saline groundwater was closer to the surface than the down-dip Mobile Bay Field which inhibited vegetation growth. This resulted in more active dunes and increased sand grain remobilization that led to increased clay coat abrasion and hence, discontinuous to no clay coat formation.

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Introduction

One goal in oil and gas exploration is to enhance regional and field-scale reservoir quality prediction models (Hohn, 1998). In these models, the impact of diagenesis on sandstone reservoir quality at great burial depths can be difficult to constrain (Ryu et al., 1999). Diagenetic processes that reduce interstitial open pore space include compaction during burial, along with cementation resulting from the formation of authigenic minerals as the pore waters reach chemical equilibrium in the diagenetic environment (Dixon et al., 1989). However, diagenesis may create secondary porosity by the dissolution of framework grains and/or cements, which can be a contributor to the exceptional porosity values observed in some deeply buried sandstone reservoirs (Bjorlykke, et al., 1989).

Diagenesis can often result in reduced intergranular porosity and low reservoir quality of deeply buried sandstones; however, many exceptions exist. One such exception is the Oxfordian Norphlet Formation sandstone, which forms a prolific hydrocarbon play that spans across Louisiana, Mississippi, Alabama, Florida, and the shallow offshore of the eastern Gulf of Mexico (EGoM) (Ajdukiewicz et al., 2010). Past research indicated that eolian dune facies within the Norphlet Formation forms the primary reservoir facies for oil and gas (Mancini et al., 1985; Ajdukiewicz et al., 2010). However, porosity within the Jurassic Norphlet Formation has a high degree of heterogeneity and so represents a major risk to petroleum exploration in this play. For instance, mean porosity of Norphlet Formation eolian sandstones in the Mobile Bay region is approximately 23%, which is ~ 5% to 15% higher than porosities observed in sand flat sandstone facies the upper Norphlet Formation (Mancini et al., 1985; Schmoker et al., 1994).

Intensive investigation of the Norphlet Formation in the Mobile Bay area indicated diagenetic clay coatings surrounding quartz grains in eolian dune sandstones likely inhibited the growth of authigenic quartz cement, resulting in the preservation of open pore space within the intergranular volume (IGV, i.e., the sum of intergranular porosity, matrix, and cement present between framework grains) (Ajdukiewicz et al., 2010). However, these clay coats have not been clearly documented in eolian dune sandstones in other regions where the Norphlet Formation also exhibits high porosity in deeply buried reservoir sandstones (Kugler et al., 1990; Ajdukiewicz et al., 2010). The Flomaton Field (Figure 1), which represents the first significant gas discovery in the Norphlet Formation of Alabama, preserves proximal Norphlet deposits shed from the remnant Alleghany Highlands to the northeast (Weislogel et al., 2015; Gutierrez, 2016; Hunt et al., 2017). Structurally, the Flomaton Field formed on a NW-SE trending anticline adjacent to a low-relief salt feature and is bounded to the south and west by the Pickens-Gilberton-Pollard regional fault system (Keyes, 1971; Marzano et al., 1988). This study analyzes the sedimentology and paragenesis of the Norphlet Formation strata from the Flomaton Field in Escambia County, southeast Alabama in order to assess the controls on high primary porosity in Norphlet Formation reservoir sandstones in this proximal basin margin area compared to the central part of the Norphlet erg in the Mobile Bay area.

Figure 1: Structural map of southern Alabama showing the location of the Flomaton Field (Modified from Mancini et al., 1992).

Geologic Setting and Norphlet Formation Deposition

Formation of the Gulf of Mexico (GoM) basin initiated during the late Triassic rifting of Pangea (Van der Voo et al., 1976). The paleoenvironment of the EGoM region consisted of the interior of a large landmass with hyper-arid desert conditions that was in part due to the orographic effect of the Appalachian Mountains to the north and east (with respect to current coordinates), which served as a barrier for air and water circulation to the GoM region (Salvador et al., 1987). During the Oxfordian, Norphlet Formation eolian sandstone was deposited as part of a large erg system that occupied the eastern part of the GoM, forming an extensive and highly economical conventional sandstone reservoir fairway in the EGoM (Figure 2; Winker et al., 1988). In the southwestern EGoM, rifting allowed seawater to enter the restricted Gulf of Mexico (Mancini et al., 1984; Marton et al., 1999), and by late stage Norphlet deposition, a marine transgression occurred in the EGoM, which caused reworking of the Upper Norphlet and subsequent deposition of the algal carbonate mudstones of the overlying Smackover Formation (Figure 3; Mancini et al., 1985). Burial during the Late Mesozoic led to thermal maturation of

Smackover source rocks, which charged the Norphlet reservoir with hydrocarbons at approximately 104 Ma (Mudford et al., 1995).

Figure 2: A paleogeographic reconstruction of the ancestral Gulf of Mexico and the approximate location of the Norphlet erg in the Middle Jurassic (Douglass, 2011; modified from Ron Blakey, 2010).

Age	Period	Epoch	Stage	Rock Unit
145	Jurassic	Lower Cretaceous	Berriasian	Cotton Valley Group
			Tithonian	
151				
		Upper	Kimmeridgian	Haynesville Formation
156				Buckner Anhydrite Member
				Smackover Formation
160			Oxfordian	Norphlet Formation
	Middle	Callovian		Pine Hill Anhydrite Member
164				Louann Salt
				Werner Formation
200	Upper Triassic		Rhaetian	Eagle Mills Formation
	Paleozoic Basement			

Figure 3: Stratigraphic column of southern Alabama and the Mobile Bay region (Hunt, 2013).

The onshore boundaries of the Norphlet erg deposits are well constrained in the southeastern US due to decades of oil exploration and exploration activity (Figure 4; Marzano et al., 1988; Ajdukiewicz et al., 2010). Whereas maximum Norphlet thickness is approximately 1,350 ft in offshore areas of the EGoM, onshore it is much thinner, with a total thickness of 500 ft in southern Alabama, 1,000 ft in Mississippi, and 400 ft in the Florida panhandle (Figure 5; Dixon et al., 1989). In the Flomaton Field study site in southwest Alabama, the average Norphlet Formation thickness is approximately 400 ft, ranging from 50-800 ft (Higginbotham et al., 1990). Across the EGoM region, the Norphlet Formation is buried at depths ranging from 9,800 ft in Mississippi to 22,000 ft in the shallow offshore areas of the EGoM (Rice et al., 1992). The average burial depth of the Norphlet Formation in the Flomaton Field ranges from 14,000 ft to 17,000 ft (Higginbotham et al., 1990; Rice et al., 1992).

Figure 4: Interpretation of Norphlet Formation maximum extent across Mississippi, Alabama, Florida, and parts of the shallow Gulf of Mexico (Hunt et al., 2017).

Figure 5: Norphlet net sand isopach map across the EGoM region (Marzano et al., 1988).

Norphlet Diagenesis

Other pre-Tertiary sandstones buried as deeply as the Norphlet Formation have porosities of ~ 6%; however, porosities of Norphlet reservoirs range up to 23% (Dixon et al., 1989).

Models and empirical data show mechanical compaction of sandstones during burial cause rapid decline of IGV, from ~40% at the surface to ~28% at 5,000 feet (Dixon et al., 1989, Paxton et al., 2002). From 5,000 to 8,200 feet, the IGV declines at a slower rate, until framework sediment grains stabilizes, preserving IGV of ~ 26% at depths exceeding ~8,200 ft (Paxton et al., 2002). No further significant decrease in IGV is observed occur down to 21,000 ft unless grains experience ductile deformation (Paxton et al., 2002). Therefore, mechanical compaction can typically reduce IGV to an average of 26% in most rigid-grain sandstones (Paxton et al., 2002).

Deeply buried porous sandstones of the Norphlet reservoir, commonly preserve intergranular porosities up to 25%, which suggests a lack of both ductile grain deformation and

cementation to reduce the intergranular pore space (Dixon et al., 1989; Paxton et al., 2002). In the Mobile Bay, porous reservoir sandstones are overlain by the Upper Tight Zone (UTZ), a low-porosity (~8%) 10-190-foot-thick interval, which is characterized by abundant quartz cementation (Mancini et al., 1985; Marzano et al., 1988; Paxton et al., 2002; Ajdukiewicz et al., 2010). Strata of the reservoir zone and the UTZ are compositionally and texturally similar (Wilkerson, 1981). The vast majority of samples taken from wells across the EGoM show a subarkose composition (Figure 6) according the classification of (Folk, 1974). This suggests that porosity variability within the Norphlet Formation is not related to compositional variability of the reservoir rock (Marzano et al., 1988).

Figure 6: Left figure shows a ternary diagram (Wilkerson, 1981) illustrating the petrographic composition of the Norphlet Formation according to the classification of (Folk, 1974). Right figure depicts the distribution of the quartzose lithofacies in southern Alabama (Wilkerson, 1981).

Petrographic analysis indicates porosity preservation in reservoir sandstones below the UTZ in Mobile Bay is controlled by well-developed diagenetic clay coats surrounding quartz sandstone grains that prevented significant cementation (Dixon et al., 1989; Pittman et al., 1992; Ajdukiewicz et al., 2010). These clay coats inhibit quartz overgrowths and cement growth by physically blocking nucleation sites on host detrital quartz grains (Pittman et al., 1992;

Ajdukiewicz et al., 2010; Wooldridge et al., 2017). Previous studies of eolian sandstone reservoirs, including the Rotliegende Formation in Europe as well as the Unayzah Formation in the Middle East, concluded that authigenic chlorite clay coats are the most effective clay mineral for preventing intergranular cementation in quartz sandstones (Paxton et al., 2002; Ajdukiewicz et al., 2010; Wooldridge et al., 2017).

Two primary types of clay coats have been identified in the eolian sandstone of the Norphlet Formation in Mobile Bay: authigenic chlorite coats and tangential clay coats (Ajdukiewicz et al., 2010). Authigenic chlorite coats likely originate as saponite, which formed on grain surfaces of dune deposits that were submerged by hypersaline groundwater (Ajdukiewicz et al., 2010; Wooldridge et al., 2017). Saponite commonly occurs as the precursor to chlorite in arid eolian environments in hypersaline brines (Kugler et al., 1990). The saponite eventually transformed into high-temperature chlorite during burial (Ajdukiewicz et al., 2010). Tangential coats on the other hand, formed when clays in suspension in meteoric rainwater or floodwater infiltrated into the sand of the vadose zone above the water table. Repeated wetting, infiltration, and drying cycles have the ability to create multilayered continuous coats on sand grain surfaces (Dixon et al., 1989; Ajdukiewicz et al., 2010). In the Norphlet UTZ sandstones, the tangential clay coats show significant discontinuities that formed due to coat abrasion when coated grains in the vadose zone were remobilized by eolian transport (Figure 7) (Ajdukiewicz et al., 2010). Ultimately, these discontinuities permitted the growth of quartz cement, which decreased porosity of the Norphlet UTZ (Ajdukiewicz et al., 2010; Wooldridge et al., 2017). In contrast, the sands in the phreatic zone were not subjected to reworking, allowing preservation of

the continuous tangential coats (Figure 7), forming the high porosity reservoir pay zone in the Norphlet Formation.

Figure 7: A schematic model of clay coat development and its suggested relationship to the ancient Norphlet water table which separates the vadose zone from the phreatic zone (Ajdukiewicz et al., 2010)

This study aims to evaluate the applicability of the Mobile Bay diagenetic model of Ajdukiewicz et al. (2010) to the onshore Flomaton Field, which is an area with a different geological setting and thinner interbeds of heterogenous facies. Specifically, this study will examine Norphlet sandstones for pore space, cement abundance, intergranular volume, and the presence of clay coats to compare controls on porosity in the Flomaton Field versus the Mobile Bay Field.

Methods

Sampling Overview

This study includes a sedimentologic and petrographic study of four cores of the Norphlet Formation in the Flomaton Field available from the Alabama Geological Survey (AGS; Figure 8). The four wells analyzed in this study were initially drilled between 1971 and 1985. Of these four wells, one was productive (Permit #4543) with a total oil and gas production of 332,211 (bbls) and 333,528 (mcf) respectively between 1985 and 1995 (Alabama Geological Survey, 2019; Figure 9); the remaining wells were plugged and abandoned. The depths of the sampled cores ranged from 15,018 to 16,085 feet and total core in the study totaled 525 feet (Table 1). From the four Norphlet cores, a total of 47 standard thin-sections were acquired from the AGS. These thin sections were prepared with blue epoxy to highlight the pore space.

Figure 8: Map showing the locations of the four Norphlet cores used in the study within the Flomaton Field in Escambia County, Alabama (from the Alabama Geological Survey).

Figure 9: Total well production for permit #4543 in the Flomaton Field, AL from when the well spudded in 1985 until 1994 when the well was plugged within the Norphlet reservoir (Alabama Geological Survey). It is the only well of the four studied that produced hydrocarbons.

Table 1: Well Information and Characteristics of the Four Studied Cores from the Norphlet Formation: Flomaton Field, AL

Permit	API Number	Well Name	Core Depth (ft)	Latitude	Longitude	Production	Thin-Sections
1674	01-053-20035-00-00	Digman 31-6 #1	15,735-16,085	31.09384	-87.50772	Dry Hole	27
3402	01-053-20169-00-00	Myrick Gas Unit 2 #1	15,510-15,607	31.06831	-87.28173	Dry Hole	8
3793	01-053-20192-00-00	Scott Paper Co #2	15,860-15,918	31.08224	-87.48315	Dry Hole	4
4543	01-053-20236-00-00	Northrup 32-3 #1	15,018-15,061	31.09635	-87.28897	Oil: 332,211 BBLS Gas: 333,528 MCF	5

Core Analysis

A total of 525 feet of core from four Norphlet wells (Table 1) at the AGS in Tuscaloosa, Alabama were logged at the cm scale using a ruler, grain size card, HCl for carbonate detection, hand lens, and sedimentary logs reflect grain size, composition, sedimentary structures, and fossils. This information was used to identify and describe four primary facies, which were then used to determine the environment of deposition (Table 2). Digital logs were constructed using the Sedlog software and associated thin-sections.

Grain Size

The 47 Norphlet thin-sections were used to document textural attributes such as grain size, roundness/sphericity, and intergranular attributes including porosity, cement, and IGV. To assess grain size distributions for each thin-section, the average diameter of approximately 100 grains per thin-section (Farr et al., 2018) were measured using a Nikon NIS-Elements image analysis software. Grain size measurements were classified using the Udden-Wentworth grade scale. The results of the grain size measurements were analyzed and compared using cumulative frequency distributions for each facies.

Porosity Analysis

Porosity (ϕ) was assessed by using the Nikon NIS-Elements image analysis software to quantify pore area for a representative field of view at 10X magnification (Figure 10). This was repeated at five locations on each thin-section that best represented the entire thin-section. Mean porosity values were determined from the cumulative results of the five areas analyzed for each thin-section. For each area on the thin section, the total area of pore space (A_{ps}) was divided by the area of the field of view (A_{fv}) to yield the percent porosity (Equation 1). The porosity

measurements were plotted with depth for each well and mean total porosity was compared among of the four facies identified from core analysis.

$$\phi = \frac{\sum_i^k A_{ps}}{A_{fv}} \quad \text{Equation 1}$$

Figure 10: One location in Norphlet thin-section (15,033 ft) taken from Core #4543 showing 13% total porosity. The green outline represents the boundary used for the area calculations. This image was taken in plane polarized light.

Intergranular Volume (IGV) and Cement Measurements:

The IGV is determined as the sum of the intergranular pore space, intergranular cement, and matrix (Paxton et al., 1991). IGV was calculated by subtracting the total area of framework sediment grains (A_g) from the area of the field of view (A_{fv}) (Equation 2). Total pore space (A_{ps}) was determined by measuring the area of blue epoxy. Because cement can be optically

heterogeneous, it is difficult to document directly using basic image analysis techniques.

Therefore, the area of the cement was approximated as the residual obtained from subtracting pore space from the IGV (Equation 3). Since the matrix area in the Norphlet thin-section samples were negligible, the area of the cement and matrix value effectively represented the cement area for use in calculations of compactional and cementational porosity loss.

$$\mathbf{IGV} = \mathbf{A_{fv}} - \mathbf{A_g} \quad \text{Equation 2}$$

$$\mathbf{Area\ of\ Cement\ and\ Matrix} = \mathbf{IGV} - (\mathbf{A_{ps}}) \quad \text{Equation 3}$$

Compactional/Cementational Porosity Loss

The compactional porosity loss (COPL) is the amount of original porosity lost by compactional processes which is expressed as a percentage of original rock volume (Ehrenberg et al., 1989). The COPL can be estimated by Equation 4 (Lai et al., 2015):

$$COPL = OP - \frac{(100 \times IGV) - (OP \times IGV)}{(100 - IGV)} \quad \text{Equation 4}$$

The OP term represents original depositional porosity, which has been estimated by previous studies of reservoir sandstones in southern Alabama at approximately 40%; however, this original depositional porosity varies for each facies based on grain size and sorting attributes (Lai et al., 2014). Therefore, eolian dune facies original porosity was estimated to be 40%, sand flat and nearshore facies at 30% and wadi facies at 35%, based on comparisons with studies relating sand texture to depositional porosity from Ehrenberg (1989) and Lai et al., 2014). These

estimations have an error of approximately +/- 5%. The cementational porosity loss (CEPL) can be estimated using Equation 5 (Lai et al., 2014).

$$CEPL = (OP - COPL) \times \frac{CEM}{IGV} \quad \text{Equation 5}$$

In this equation, OP represents the original porosity loss, COPL is the porosity loss due to compaction, and CEM represents the total cement area percentage of the thin-section.

Clay Coats

Clay minerals surrounding the perimeter of quartz grains were identified under a petrographic microscope (Figure 11). Where present, the length of the clay coats were measured as well as the estimated percentage of coverage of the entire grain perimeter for each thin-section. The mean clay coat coverage was estimated by taking the mean coverage percentage within the field of view at five locations on the thin-section. The facies that exhibited clay coats in thin-section were noted and clay coat abundance was plotted with respect to total porosity.

Figure 11: Norphlet thin-section in plane polarized light from a depth of 15,080 ft from Core #4543 showing the clay coats on the perimeter of the quartz grains highlighted in green. Discontinuous coats were documented by recording separate length measurements for each segment.

Results

Lithofacies of the Norphlet Formation Recorded in the Flomaton Field

Four distinct facies were identified based on differing lithology, texture, sedimentary structures, and fossils (Table 2).

Table 2: Norphlet Core Facies Descriptions		
Lithofacies	Lithology and Structures	Environment Interpretation
Facies 1	Light tan-dark grey/purple/red color, fine to coarse-grained, moderately-poorly sorted sandstone, massive texture present in small sections, thin laminae with 1-3 mm thick repeating horizontal laminations that contain a poorly sorted mix of grain sizes, faint cross stratification with 1 cm quartz pebbles	Wadi
Facies 2	Light-dark tan, reddish, moderately well-very well sorted fine-medium grain sandstone, 1-2 mm thick horizontal laminations, rare crinkly laminations, abundant quartz pebbles, presence of stylolites, possible burrows	Sand Flat
Facies 3	Grey to dark grey well to very well sorted limey-sandstone, frequent wavy laminations, less common 2-5 mm horizontal planar laminations with some laminations containing subtle wavy features, 2-3 cm clusters of spherical algal oncoids, disarticulated brachiopod shell fragments, mottled texture throughout facies, increasing degree of reddish color up-section, minor 2-3cm flame structures	Nearshore
Facies 4	Tan color, well sorted sandstone, distinct 1-4 mm low-angle pinstripe laminations, repeating bands of inversely graded laminae	Eolian Dune

Facies 1

Facies 1 consisted of a light tan-dark grey/red moderately to poorly sorted, angular to subangular fine-coarse-grained sandstone, with ~1cm diameter quartz pebbles common throughout the entire facies (Figure 12). The sandstone generally displayed upward fining beds of horizontally laminated sediment that was interbedded with some thin intervals of massive sandstone (<5cm) and less commonly 1-3 mm thick poorly sorted sandstone laminae.

Large grain size and poor sorting indicates the cross-lamination was produced by bedload transport and bedform migration due to turbulent aqueous fluid flow. Fining-upward grain size within beds are consistent with deposition by decelerating flow (Fryberger et al., 1988). The depositional environment of Facies 1 is interpreted as a wadi, which is consistent with similar facies observed in the Norphlet Formation from other cores within Escambia County (Gutierrez, 2016).

Figure 12: Facies 1 of Core #4543 from 15,052 ft showing alternating bands of poorly and well sorted grains interpreted to be a wadi environment.

Figure 13: Thin-section photograph of Facies 1 in plane polarized light taken from a depth of 15,043 ft in Core #4543.

Facies 2

Facies 2 consisted of light-dark tan, occasionally reddish, moderate-well sorted, subangular, fine to medium-grained sandstone with 1-2 mm thick horizontal laminations and crinkly laminations (Figure 14). The horizontal laminated intervals were interbedded with

massive, moderately well sorted sandstone. Facies 2 contained rare 4-5 mm quartz pebbles that were similar to those in observed in Facies 1. Burrow structures were present but rare.

The depositional environment for Facies 2 is likely a sand flat. The horizontal lamination structures were deposited by wind ripple migration, which are common in sand flat (Kocurek, 1981). The crinkly laminations are interpreted as adhesion structures formed by the adhering of dry, wind-blown sand to a wet or damp surface during saltation (Scherer al., 2005), suggesting frequent wetting of this sandflat environment. The thickness of Facies 2 across the sampling region is much greater compared to the thickness of the other 3 facies (Table 3), and this preservation may have been enhanced by frequent wetting of these deposits.

Figure 14: Facies 2 of core #1674 from 15,547 ft, displaying horizontal and crinkly laminations.

Figure 15: Thin section photograph of Facies 2 in plane polarized light taken from a depth of 15,764 ft.

Facies 3

Facies 3 consisted of dark grey, very fine-grained, calcareous sandstone that contained well sorted and subrounded quartz grains along with brachiopod shell fragment 0.5-4 cm in diameter (Figure 16) and distributed fairly evenly throughout the facies. Additionally, clusters of 2-3 cm oncoids were noted alongside the brachiopod shell fragments in core #3793. Wavy bedding was the dominant sedimentary structure in Facies 3 with thin interbedded rippled sandstone and mud layers. Wavy bedding is a record of alternating high and low velocity flow conditions (Martin, 2000). The sandier portions are deposited when the water flow is relatively fast ($<0.5\text{m/s}$), whereas the muddier/calcareous layers are deposited during intervals of slack to stagnant water (Carlisle et al., 2010).

Flame structures 1.0-1.5 cm wide are observed at some bedding contacts. Flame structures form when the weight of the overlying bed forces the underlying bed to push up through the overlying bed, generally when both strata are saturated with water (Anketell et al., 1970), which indicates a rapid sedimentation rate. The presence of flame structures, wavy laminations, and fossils that suggest subaqueous deposition in a nearshore, tidally influenced marine environment. Finally, stylolites were common and evenly dispersed throughout Facies 3 (Figure 16).

Figure 16: Facies 3 of core #1674 from 15,838 ft displaying horizontal laminations with brachiopod shell fragments and stylolites.

Figure 17: Thin section photograph in plane polarized light of Facies 3 taken from a depth of 15,863 ft in Core #1674 displaying sutured grain contacts.

Facies 4

Facies 4 consisted of a light tan colored, well sorted subangular, fine-grained sandstone with high-angle (15-20°) pinstripe laminations (Figure 18). The high-angle pinstripe laminae were ~1-4 mm thick, displayed inverse grading, and was consistently present throughout the facies. Inversely graded pinstripe lamination results from grain sorting in migrating eolian dunes, where finer grains are deposited first and coarser sediments with greater momentum in the grain flow are deposited on top of finer grains along lee slopes of dunes (Fryberger and Schenk, 1988; LeTourneau et al., 2006). Also, grainfall deposition results in finer suspended load deposits interlaminated with grainflow laminations (Besly et al., 2017). Inclined pinstripe laminations are consistent with an eolian dune depositional environment, which are recognized commonly in Norphlet deposits around the EGoM (Ajdukiewicz et al., 2010; Gutierrez, 2016).

Figure 18: Facies 4 (eolian dune) of Core #4543 from 15,038 ft showing inclined inversely graded pinstripe laminations.

Figure 19: Thin-section photograph of Facies 4 in plane polarized light taken from a depth of 15,033 ft from Core #4543 displaying high porosity visible as areas of blue-dyed epoxy.

Core Stratigraphy

The four facies identified in the Norphlet Formation occurred in different abundances within the four cores (Table 3). The sand flat facies occurred most frequently, totaling 233 feet whereas the eolian dune facies only accounted for 17 feet, or 3% of the total core analyzed. Core #3793 lacked wadi facies, Core #4543 lacked sand flat and nearshore facies, and Core #1674 lacked eolian dune facies.

In Table 3, the cores are arranged as they occur from west to east in the Flomaton Field. The nearshore and sand flat facies are more abundant in the west while the wadi facies is more abundant in east of the Flomaton Field. The eolian dune facies exists in small intervals throughout the sampled cores and is absent in Core #1674 on the western edge.

Table 3: Norphlet Core Facies Thicknesses					
	Core 1674	Core 3402	Core 3793	Core 4543	Total
Facies 1: Wadi	24 (7%)	18 (44%)	0 (0%)	38 (88%)	80
Facies 2: Sand Flat	206 (60%)	13 (32%)	14 (15%)	0 (0%)	233
Facies 3: Nearshore	115 (33%)	7 (17%)	73 (76%)	0 (0%)	195
Facies 4: Eolian Dune	0 (0%)	3 (7%)	9 (9%)	5 (12%)	17
Total	345	41	96	43	525

Core #4543

Figure 20: Digital core log of Core #4543 sampled from the Flomaton Field.

Core #3402

Figure 21: Digital core log of Core #3402 sampled from the Flomaton Field.

Core #3793

Core #1674

Figure 23: Digital core log of Core #1674 sampled from the Flomaton Field.

Petrography of the Norphlet Formation

Textural Attributes and Cement Mineralogy

Grain size distributions for each of the four Norphlet facies were compared using a cumulative frequency plot (Figure 24). Overall, the majority (~52%) of Norphlet grains were categorized as fine-grained sand (0.125-0.250 mm), with fine-grained sand being the most abundant grain size in the sand flat and eolian dune facies. The wadi facies contained mainly medium sand grains (~19%) and coarse sand grains (~51%), whereas the nearshore facies consisted of mainly fine sand (~83%).

Figure 24: Cumulative frequency curves for each of the four Norphlet facies.

Major pore types exhibited in the Norphlet Formation deposits include intergranular (Figure 25), fracture (Figure 27), and dissolution (Figure 28). Overall, intergranular porosity was the most common pore type in the wadi, sand flat, and eolian facies. Grain contact types include tangential (Figure 29), long (Figure 30), sutured (Figure 31), and concavo-convex (Figure 32), and some grains were free-floating (Figure 33). Long grain contacts were most abundant in the wadi and sand flat facies, suggesting compaction was not inhibited with burial. The nearshore facies exhibited sutured contacts as the primary grain contact type, indicating limited cement and significant compaction reducing intergranular pore space. The eolian dune facies was the only facies to exhibit mainly tangential grain contacts and free-floating grains, suggesting compaction was inhibited by cement filling intergranular pore space. Cement types were primary quartz and calcite, with quartz being the most dominant cement in all facies except the nearshore facies, which also included abundant calcite cement (Table 4).

Table 4: Norphlet Facies Petrographic Textural Attributes					
	Primary Pore Type	Secondary Pore Type	Primary Contact	Secondary Contact	Primary Cement Type
Facies 1: Wadi	Intergranular (90%)	Dissolution (10%)	Long (95%)	Concavo/Convex (5%)	Quartz
Facies 2: Sand Flat	Intergranular (98%)	Dissolution (2%)	Long (70%)	Tangential (30%)	Quartz
Facies 3: Nearshore	Fracture (95%)	Dissolution (5%)	Sutured (90%)	Concavo/Convex (10%)	Quartz/Calcite
Facies 4: Eolian Dune	Intergranular (99%)	Dissolution (1%)	Tangential (85%)	Free-Floating (15%)	Quartz

Figure 25: Norphlet thin-section in plane polarized light taken from a depth of 15,080 ft from core #4543 in the eolian dune facies showing intergranular porosity. Intergranular porosity was the dominant type of porosity encountered in Norphlet thin-sections.

Figure 26: Norphlet thin-section in plane polarized light taken from a depth of 15,080 ft from core #4543 in the wadi facies showing channel dissolution pores (red circles).

Figure 27: Norphlet thin-section in plane polarized light taken from a depth of 15,607 ft from core #3402 in the nearshore facies that shows fracture porosity indicated by the vein of blue epoxy.

Figure 28: Norphlet thin-section in plane polarized light taken from a depth of 16,084 ft from core #1674 in the wadi facies showing dissolution (secondary) porosity indicated by the red circle.

Figure 29: Norphlet thin-section in plane polarized light taken from a depth of 15,033 ft from core #4543 in the eolian dune facies showing tangential (point) grain contacts (red arrows).

Figure 30: Norphlet thin-section in plane polarized light taken from a depth of 15,593 ft from core #3402 in the sand flat facies showing a long grain contact (red lines).

Figure 31: Norphlet thin-section in plane polarized light from a depth of 15,863 from Core #1674 in the nearshore facies showing quartz grains that are sutured (red circles).

Figure 32: Norphlet thin-section in plane polarized light taken from a depth of 16,062 ft from core #1674 from the wadi facies showing a concavo-convex grain contact (red circle).

Figure 33: Norphlet thin-section in plane polarized light taken from a depth of 15,033 ft from core #4543 in the eolian dune facies showing a free-floating grain (red circle) surrounded by abundant pore space.

Clay Coats

Well-developed clay coats were observed in ten thin-sections from the sand flat facies and both thin-sections from the eolian dune facies. These well-developed clay coats were only present in thin-sections of fine-sandstone, specifically with grain size ranging on average from 0.19-0.23 mm. Of the eolian dune facies thin-sections that showed evidence for clay coats, only ~5-10% of the grains exhibited well-developed clay coats. For the 10 thin-sections of the sand flat facies that contained grains with clay coats, only ~3% of the grains exhibited well-developed clay coats. No quartz grain displayed a full 100% well-developed clay coat grain coverage, though the eolian dune facies had grains with ~80% of the perimeter covered with clay coat cement. Percentage of the quartz grain perimeter covered by clay coats increased with a decrease in mean cement percentage (Figure 34). However, increased grain perimeter clay coat coverage does not correlate with total porosity (Figure 35). In two samples from the sand flat facies grains with clay coats only exhibited clay coats around >20% of the grain perimeter and

had a total porosity of ~12-14%. Other sand flat facies had much higher perimeter coverage (~50%) but just slightly higher porosity of ~16%. The eolian dune facies had the highest grain perimeter coverage of >80%, but also had a porosity of ~16% (Figure 34).

Figure 34: Scatter plot showing the relationship between thin-sections with quartz grains that are partially coated with clay coatings and their respective cement abundance present in the thin-section. All values are a mean of the thin-section. Only the eolian dune and sand flat facies exhibit evidence of clay coats in this study.

Figure 35: Scatter plot showing the relationship between the thin-sections with quartz grains that are partially coated with clay coatings and the respective porosity percentage observed in the thin-section. All values are a mean for each thin-section.

Total Porosity

The total porosity density distribution for the 47 Norphlet thin-sections was characterized by 235 total porosity measurements (5 areas measured per thin-section) (Figure 36). The eolian dune facies demonstrated considerably higher porosity values (mean = 16.2%) than all other facies and was also associated with 16 grains with ~80% clay coat coverage. The nearshore facies was characterized by distinctly low porosity values (mean = 2.4%) while the sand flat and wadi facies exhibited overlapping porosity values that averaged 7.1% and 4.9% respectively (Figure 37).

Figure 36: Kernel density distribution plot of the four Norphlet Formation facies with a combined bar plot showing the spread of total porosity; n=235.

Figure 37: Scatter plot showing the mean total porosity for each thin-section of the four Norphlet Formation facies; n=47.

Cement Abundance and Petrography

The kernel density distribution for cement abundance depicts a bimodal distribution, with the eolian dune and nearshore facies as lower end member ($<5\%$) whereas the wadi and sand flat facies are upper end members ($>8\%$) (Figure 38). Eolian dune facies cement abundance is the lowest with an average of 0.9% compared to the sand flat facies with the highest cement abundance with an average of 12.6%. The sand flat and wadi facies display intermediate cement abundances averaging around 12%. Mean total cement for each Norphlet thin-section plotted with respect to depth reveals that depth is not correlated with cement abundance, and that cementation shows the greatest correlation with facies (Figure 39).

Figure 38: Kernel density distribution plot of the four Norphlet Formation facies with a combined bar plot showing the spread of cement abundance; $n=235$.

Figure 40: Sand flat thin-section taken from a depth of 15,590 ft from core #3402 in plane polarized light displaying a meniscus cement (red circle) and a pendent cement (orange circle).

Intergranular Volume (IGV)

The Norphlet IGV values showed narrower ranges than porosity and cement abundances (Figure 41). The nearshore facies had a distinctly lower IGV values (mean = 4.1%), whereas the eolian dune, sand flat and the wadi facies had a much higher IGV values. The sand flat facies had the highest mean IGV of all facies at 19.7% (Figure 42). The wadi facies marked the largest variability in IGV with a standard deviation of 1.8 compared to 1.0, 0.7, and 0.1 of the sand flat nearshore, and eolian dune facies respectively. Overall, higher IGV values correlated with higher total porosity values.

Figure 41: Kernel density distribution plot of the four Norphlet Formation facies with a combined bar plot showing the distribution of IGV values; n=235.

Figure 42: Scatter plot showing the mean IGV with depth for each thin-section of the four Norphlet Formation facies. The size of the point is scaled to the total porosity; n=47.

COPL & CEPL

Compactional porosity loss (COPL) and cementational porosity loss (CEPL) were estimated for each of the Norphlet thin-sections (Figure 43). Each facies displays distinct COPL/CEPL clusters where each cluster represents a different path to porosity reduction. Mechanical compaction was more important than cementation in reducing porosity in the eolian dune, nearshore, and wadi facies compared to the sand flat facies, which reflects greater porosity loss due to cementation. COPL and CEPL were also plotted with respect to porosity which suggests that the nearshore and eolian dune facies were not subject to intense cementation (Figure 44a, Figure 44b).

Figure 43: Scatter plot showing COPL vs CEPL for the 235 measurements of 47 Norphlet thin-sections.

Figure 44: (a) Scatter plot showing porosity vs COPL for the 235 measurements of 47 Norphlet thin-sections. (b) Scatter plot showing porosity vs CEPL.

Discussion: Norphlet Paragenesis in the Flomaton Field

The results reveal varying paragenetic evolution of the four facies in the Norphlet Formation samples within the Flomaton Field (Figure 45). Of these four facies, only the eolian dune facies is a viable reservoir which is due to its distinct diagenetic evolution. The eolian dune facies showed high porosity values associated with low cementation that filled moderate IGV. The eolian dune diagenetic facies displayed the lowest CEPL values with a mean of 1.1% which indicates compaction and cementation had minimal influence on the observed eolian dune pore structure. The low COPL and CEPL and IGV values for the eolian dune samples supports the hypothesis that the high porosity exhibited by the eolian dune facies was caused by an early introduction of cement, prior to compaction, that tended to keep the grains apart during eogenesis (Taylor et al., 2010; Pohl, 2011).

The eolian dune facies was the only facies to exhibit free-floating grains and had among the highest IGV, indicating compaction was suppressed due to the presence of an early evaporite cement. Halite and other evaporite mineral cement have been suggested as a dominant early cement type in the onshore fields of the Norphlet Formation such as the Hatter's Pond field

(Honda & McBride, 1981; Higgenbotham et al., 1990; Vaught et al., 1998). The paleographic location of the Norphlet Erg under arid depositional conditions facilitated this early diagenetic impact on the Norphlet Formation (Vaughn et al., 1988; Ajdukiewicz et al., 2010). In addition, the Norphlet Formation lies directly above the Louann Salt (Dixon et al., 1989). The presence of anhydrite in the upper Louann Salt and halite in the lower part of the Louann Salt resulted in formation water with high salinity that precipitated a salt cement in Norphlet Formation sandstone (Schenk & Schmoker, 1993). Furthermore, the Norphlet was overlain by impermeable mudstone of the lower Smackover Formation that isolated it from other formation waters (Claypool & Mancini, 1989). This isolation from other younger dewatering formations during early burial allowed the preservation of salt cements (Figure 45; McBride et al., 1987; Kugler et al., 1990; Schenk & Schmoker, 1993). Later, porosity within the IGV formed during the leaching of the cements at depth in the later stages of diagenesis, which resulted in reservoir quality pore structures (Figure 45; Marzano et al., 1988; Ajdukiewicz et al., 2010).

Rare (~5-10% of grains) but quite continuous (>80% grain coverage) clay coats were also formed during early burial in the eolian dune facies. These tangential coats were formed when clays in suspension in rainwater or floodwater were infiltrated into the sand above the water table. The remobilization of the coated grains in the vadose zone led to coat abrasion and resulted in significant discontinuities in the protective coats and formed discontinuous abraded coats (Ajdukiewicz et al., 2010).

All other facies of the Norphlet Formation exhibit low porosity. The sand flat facies showed low porosity due to high cementation that filled high IGV. This indicates that the sand flat facies was also subject to early cementation (Figure 45), but petrographic evidence indicates a different style of early cementation compared to the eolian dune facies. Early meniscus and

pendant cement formed in the sand flat facies, indicating vadose zone cementation by water trapped around grains (Dunham et al., 1971). Meniscus cements are commonly formed in meteoric setting where sediment wetting occurred during frequent water table fluctuations or from rainwater which percolated down through the sand (Schenk et al., 1988). The pendant (gravitational) cement type which existed on the stratigraphic bottom of quartz grains were likely formed by the precipitation of water droplets in the vadose zone (Dunham et al., 1971). The occurrence of both meniscus and pendent cements indicate that the sand flat facies of the Norphlet Formation experienced early vadose zone cementation. This early cementation potentially could have caused a decrease in open pore space, lowered porosity, and also preserved intergranular volume. With further burial, compaction resulted in a decrease in pore space. However, the abundance of meniscus and pendent cements existed on $< \sim 15\%$ of the grains. Therefore, there may not have been a sufficient volume of cement to prop open the pores. If this was the case, then there potentially could have been an early evaporite cement that filled the pores after the formation of the meniscus and pendent cements.

Both the eolian dune and sand flat facies were subject to late cement dissolution (Figure 45), which resulted in increased porosity. Thermomaturation of organic matter in the overlying Smackover Formation produced carboxylic acids and hydrogen sulfide (Vaughn et al., 1988; Dixon et al., 1989). The introduction of these components into the Norphlet system likely resulted in widespread dissolution of not only early cements in the eolian dune and sand flat facies, but framework grain dissolution as well which opened up additional pore space in middle to late-stage diagenesis. Due to thermomaturation processes, late carbonate cements were not present (Dixon et al., 1989).

Wadi facies similarly exhibited low porosity with high cementation, though it yielded intermediate IGV values due to a lesser degree of early cementation compared to the eolian dune and sand flat facies. The early cement in the wadi facies inhibited compaction during burial which preserved the IGV which was partially filled by quartz cementation within the IGV, followed by the development of minor porosity (~2%), which was the primary factor in defining the pore structure. Dissolution, particularly of feldspars, was responsible for almost half of the 7% mean total porosity measured within the wadi facies. Dissolution was likely the result of migrating fluids rich in CO₂ and organic acids associated with hydrocarbon maturation (Marzano et al., 1988). Some dissolution pores were partly filled with quartz and minor calcite cement in the wadi facies, reflecting a minor late-stage cementation event.

The sand flat and wadi facies both had a higher mean CEPL than the eolian dune facies, which indicates compaction/cementation primarily contributed to porosity reduction. The wadi had a lower IGV compared to the sand flat facies due to the wadi facies not exhibiting early meniscus and pendent cementation which helped prop open pores.

In comparison, the nearshore facies exhibited a very low IGV and consequently, very low cement abundance and low porosity. This suggests that the effects of compaction and cementation primarily controlled the lack of pore structure. For this facies, burial and compaction reduced IGV until the majority of the grain contacts became sutured (Figure 45). This was facilitated by the absence of early cementation that would have preserved intergranular volume. Marine reworking contributed to the lack of early cement in the nearshore facies and is also suggested to be the case in the shallow marine sandstones of the Bridport Sandstone Formation in southern England (Bjorkum & Walderhaug, 1989). The majority of any open pore space left after compaction was subject to calcite cementation followed by silica cementation

during late-stage diagenesis. During the final stages of late diagenesis, major pressure solution and stylolitization occurred due to overburden pressure.

Figure 45: Paragenetic sequence generated from petrographic analysis for the Flomaton Field samples. Thickness of the lines indicate significance in the Norphlet samples.

Controls on Norphlet Reservoir Quality

Previous research reported that the Norphlet in Mobile Bay and other eolian sandstones that are deeply buried and lack or have poorly developed clay coats are highly cemented with authigenic quartz cement, whereas sandstones with grains that developed robust clay coats display much lower volumes of cement (Dixon et al., 1989; Bloch et al., 2002; Taylor et al., 2004; Ajdukiewicz et al., 2010). In the Norphlet reservoirs of the Mobile Bay area, continuous chlorite grain coats have been attributed to porosities exceeding 24% (Ajdukiewicz et al., 2010). Numerical models of the Norphlet Formation in Mobile Bay show that greater clay coat coverage

is required to preserve significant amounts of porosity (Bloch et al., 2002; Ajdukiewicz et al., 2010). In this field, grains need approximately 98% of the grain coated by the protective clay (either chlorite or illite) to prevent extensive quartz cementation (Taylor et al., 2004; Taylor et al., 2006; Ajdukiewicz et al., 2010; Wooldridge et al., 2017). In contrast, discontinuous coatings, which is usually formed by processes such as mechanical infiltration in vadose zone sands, are less effective in preventing quartz cementation (Wilson et al., 1977; Bloch et al., 2002).

Norphlet diagenesis documented in the Hatter's Pond Field in onshore Alabama was characterized by shallow diagenesis that produced illite coats as the first diagenetic sequence (Honda et al., 1981). Illite coats have been associated with slightly less porosity preservation than chlorite coats in Mobile Bay, although still contributing to some degree of porosity preservation (Ajdukiewicz et al., 2010). Illite coat formation was followed by early burial (before hydrocarbon accumulation) quartz overgrowths and by anhydrite and calcite cementation (Honda et al., 1981). Then, dissolution of cement and feldspars occurred during hydrocarbon accumulation. After hydrocarbon accumulation, deep diagenesis produced dolomitic cements, quartz overgrowths, and compaction pressure-solution stylolites.

In the Flomaton Field, clay coats are discontinuous and rarely present, being observed in 12 out of 47 thin-sections from the eolian dune and sand flat facies. The Flomaton grain coating coverage does not exceed 98% in any sample. The highest total perimeter coverage of clay coats occurred in the eolian dune facies, where grains with clay coats had a mean perimeter percentage of 89%, compared to 46% of the sand flat facies. Eolian dune sand grains that displayed clay coats surrounding over 90% of the grain perimeter occurred in less than ~2% of the grains in thin-sections that displayed clay coats. Yet porosity within the Norphlet of the Flomaton Field,

which consists of mostly primary intergranular porosity with a small proportion of dissolution porosity, is preserved.

Therefore, clay coat coverage percentage is not likely responsible for the porosity preservation in the Flomaton Field. There is a slight inverse correlation with the clay coat coverage and cement abundances (Figure 34) and follows the same general trend shown in previous studies (Ajdukiewicz et al., 2010; Taylor et al., 2010; Figure 46). Although these results are only from 12 thin-sections, these results suggest that with an increase in clay coat coverage, the cement abundance decreases in both the eolian dune and non-reservoir sand flat facies. However, the results also suggest that although cement abundance may slightly decrease with increased clay coat coverage, the total porosity is not affected.

Figure 46: Scatter plot showing the percent quartz surface that is coated vs the mean area of quartz cement. The plot shows samples from the Norphlet Formation in the Flomaton Field from this study (Green and Orange), Triassic sandstones from the North Sea, and samples from the Mobile Bay, AL. (Modified from Taylor et al., 2010)

The Flomaton Field is situated towards the edge of the Norphlet dune field compared to Mobile Bay which lies in the central portion of the major Norphlet dune field where larger dune heights (100s of feet) generated 100-150-foot thick eolian dune deposits (Schenk et al., 1983; Marzano et al., 1989; Schenk et al., 1990; Story et al., 1998). Norphlet reservoirs of the Mobile Bay area show extensive development of continuous chlorite grain coats, with porosity preservation associated with sandstones where 98% of grain perimeters are coated by the protective clay (Taylor et al., 2004; Taylor et al., 2006; Ajdukiewicz et al., 2010; Wooldridge et al., 2017). Smaller dune heights formed thinner beds in the Flomaton Field cores, where the mean eolian dune facies thickness was 8.5 feet. Smaller dunes in the Flomaton Field may have been more active, which resulted in increased reworking that ultimately led to more coat abrasion than what is observed in the larger, more stable dune field of Mobile Bay (Marrs et al., 1987; Ajdukiewicz et al., 2010). The coat abrasion led to discontinuous to non-existent clay coats in the Flomaton Field.

Due to the importance of early salt cements in the Flomaton Field, groundwater salinity could have played a large role in the facies paragenetic history. It has been suggested that the larger, more stable dunes of the downdip Mobile Bay Field were linear dunes and the up-dip Flomaton Field were composed of barchan dunes (Story et al., 1998). It is possible that the groundwater chemistry influenced the stabilization of these dunes. As suggested by a study in the White Sands of New Mexico (Langford et al., 2008), vegetation forms on dunes only where precipitation creates a lens of fresh water within the sand where the vegetation helps stabilize the dunes. The degree of clay coat abrasion in the Norphlet Formation reservoirs could be influenced by a shallow groundwater table and its high salinity. For example, in Mobile Bay, the accumulation of a topographic high with eolian sediments could have allowed the accumulation

of rainwater which in turn, permitted vegetation growth on the linear dunes (Langford et al., 2008). In the Flomaton Field, where topography was lower and the interdunes were located just above the saline groundwater, vegetation growth would have been restricted on the barchan dunes which possibly allowed for greater rates of sand transport and therefore, allowed a greater degree of clay coat abrasion to occur.

Thin quartz overgrowths were observed in both eolian dune thin-sections (Figure 47). It has been suggested by (Aase et al., 1996) and (French et al., 2012) that microcrystalline quartz overgrowths are effective at preserving porosity in deeply buried sandstone reservoirs by inhibiting cement growth. In the eolian dune facies, quartz overgrowths were present on more than 50% of the grains. Therefore, it is possible that these quartz overgrowths contributed to preserving porosity and inhibiting cementation after halite cements were removed. The eolian 47 dune facies quartz overgrowths could have formed as a result of initial chalcedony growth on top of a nanofilm surface-coating layer of amorphous silica similar to that of the Heidelberg Formation in Germany (French et al., 2012); however, the inhibition of cement growth could also be a consequence of the growth direction of the chalcedony that grows on the amorphous silica. This is an area of future work within the Norphlet Formation reservoirs that should include a scanning electron microscope (SEM) and electron backscatter diffraction (EBSD) analysis to form a more comprehensive quartz overgrowth regional model.

Figure 47: Norphlet thin-section in plane polarized light taken from a depth of 15,033 ft from core #4543 in the eolian dune facies showing quartz overgrowths (white circles).

Conclusion

The Norphlet Formation in the Flomaton Field exhibited four facies that displayed a high degree of heterogeneity between them in terms of pore space/structure, grain contacts, porosity, cement abundance, and intergranular volume. The major conclusions are:

- 1) Paragenesis in the Norphlet Formation is primarily facies controlled.
- 2) The preservation of porosity in the eolian dune facies resulted from an introduction of a salt cement (halite), prior to compaction, that tended to keep the grains apart during eogenesis, but was later removed due to dissolution resulting from CO₂ and organic acids associated with hydrocarbon migration. Authigenic clay coats formed early that minorly contributed to the inhibition of cement growth that helped preserve porosity at great depths.

3) In contrast with the Mobile Bay Field, clay coats were not the primary factor in porosity preservation in the eolian dune facies of the Flomaton Field. Instead, the dominant diagenetic process in the Norphlet reservoir in the Flomaton Field was salt (halite) precipitation and dissolution. The better reservoirs in the downdip Mobile Bay area experienced clay illuviation and well-developed clay coats on well-stabilized dunes that helped preserve porosity. In the updip Flomaton Field, the saline groundwater was closer to the surface which inhibited vegetation growth. This resulted in more active dunes and increased remobilization of sand grains that led to clay coat abrasion and hence, discontinuous to non-existent clay coats.

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Appendix

Table 5: Norphlet Formation Petrographical Observation Data									
Depth	Facies	Porosity	Cement	IGV	COPL	CEPL	ACOMR	ACEMR	CCD
15020	Wadi	7.8	10	17.8	27.0073	7.29927	55.5	57.43825	6.470975
15020	Wadi	6.3	10.2	16.5	28.14371	7.329341	58.75	63.02132	4.869704
15020	Wadi	5.1	9.8	14.9	29.49471	6.909518	62.75	66.91704	3.715386
15020	Wadi	5.4	9.9	15.3	29.16175	7.012987	61.75	65.86826	3.993543
15020	Wadi	4.8	10.1	14.9	29.49471	7.121034	62.75	68.89495	3.447163
15027	Wadi	3.8	9.9	13.7	30.47509	6.882966	65.75	73.27905	2.591574
15027	Wadi	3.9	9.7	13.6	30.55556	6.736111	66	72.36106	2.671946
15027	Wadi	3.7	9	12.7	31.27148	6.185567	68.25	71.9137	2.503998
15027	Wadi	4	8.7	12.7	31.27148	5.979381	68.25	69.6	2.750086
15027	Wadi	4.2	10.6	14.8	29.57746	7.464789	63	72.6525	2.931886
15033	Eolian Dune	15.8	0.3	16.1	28.48629	0.214541	59.75	1.959504	22.7963
15033	Eolian Dune	16.6	1.2	17.8	27.0073	0.875912	55.5	7.071302	23.65639
15033	Eolian Dune	15.9	0	15.9	28.65636	0	60.25	0	23.43405
15033	Eolian Dune	14.8	2.3	17.1	27.62364	1.664656	57.25	14.05868	18.75586
15033	Eolian Dune	17.1	0.7	17.8	27.0073	0.510949	55.5	4.131012	25.43469
15043	Wadi	3.8	14	17.8	27.0073	10.21898	55.5	79.50028	2.664791
15043	Wadi	4.1	13.8	17.9	26.91839	10.08526	55.25	77.98813	2.911143
15043	Wadi	4.2	15.1	19.3	25.65056	11.22677	51.75	79.099	3.033608
15043	Wadi	3	12.5	15.5	28.99408	8.87574	61.25	81.43322	1.996231
15043	Wadi	5	13.1	18.1	26.73993	9.59707	54.75	73.38936	3.68353
15057	Wadi	5.1	14.1	19.2	25.74257	10.4703	52	74.42597	3.805233
15057	Wadi	4.3	15.1	19.4	25.55831	11.24069	51.5	78.70732	3.120299
15057	Wadi	4.7	16.2	20.9	24.14665	12.28824	47.75	78.39342	3.514192
15057	Wadi	4.7	16	20.7	24.33796	12.10593	48.25	78.18226	3.506618
15057	Wadi	4.6	16.2	20.8	24.24242	12.27273	48	78.75547	3.423753
15570	Wadi	3.8	12.2	16	28.57143	8.714286	60	77.16635	2.624919
15570	Wadi	3.9	13.7	17.6	27.18447	9.975728	56	78.71301	2.740438
15570	Wadi	4	14.5	18.5	26.38037	10.67485	53.75	79.23497	2.845254
15570	Wadi	4.2	11.9	16.1	28.48629	8.510131	59.75	74.88987	2.952759
15570	Wadi	4.1	13.9	18	26.82927	10.17073	55	78.11183	2.913756
15574	Wadi	5.1	11.8	16.9	27.79783	8.519856	57.75	70.89216	3.743335
15574	Wadi	5.2	12	17.2	27.53623	8.695652	57	70.83825	3.839388
15574	Wadi	5	13.8	18.8	26.10837	10.19704	53	74.39353	3.703881
15574	Wadi	4.9	15.6	20.5	24.5283	11.77358	48.75	77.01802	3.674044

15574	Wadi	5.3	13.2	18.5	26.38037	9.717791	53.75	72.38826	3.962965
15580	Eolian Dune	14.6	0.2	14.8	29.57746	0.140845	63	1.421464	20.27173
15580	Eolian Dune	15.8	1.3	17.1	27.62364	0.940893	57.25	7.97057	21.69717
15580	Eolian Dune	16.7	2.1	18.8	26.10837	1.551724	53	11.6894	23.10159
15580	Eolian Dune	18.2	0	18.2	26.65037	0	54.5	0	29.30757
15580	Eolian Dune	16.1	0.7	16.8	27.88462	0.504808	58	4.376368	23.00777
15590	Sand Flat	6.1	14	20.1	24.90613	10.51314	49.75	70.72493	4.762837
15590	Sand Flat	6.5	13	19.5	25.46584	9.689441	51.25	67.79661	5.132392
15590	Sand Flat	7.3	14.5	21.8	23.27366	11.12532	45.5	67.64637	6.04573
15590	Sand Flat	7.4	15.6	23	22.07792	12.15584	42.5	68.93504	6.216657
15590	Sand Flat	7.6	14.2	21.8	23.27366	10.89514	45.5	66.29318	6.365523
15591	Sand Flat	7.6	13.9	21.5	23.56688	10.6242	46.25	65.81439	6.351096
15591	Sand Flat	6.8	14.5	21.3	23.76112	11.05464	46.75	69.17939	5.504763
15591	Sand Flat	6.9	14.5	21.4	23.66412	11.0687	46.5	68.86725	5.61125
15591	Sand Flat	5.9	14.2	20.1	24.90613	10.66333	49.75	71.69907	4.571904
15591	Sand Flat	6.2	13.4	19.6	25.37313	10	51	69.46604	4.841252
15593	Sand Flat	5.5	13.5	19	25.92593	10	52.5	72.09613	4.160485
15593	Sand Flat	6.1	13.9	20	25	10.425	50	70.57629	4.759071
15593	Sand Flat	6.5	16.7	23.2	21.875	13.04688	42	73.00546	5.301558
15593	Sand Flat	6.6	17.1	23.7	21.36304	13.44692	40.75	73.17073	5.431172
15593	Sand Flat	6.8	12.3	19.1	25.83436	9.122373	52.25	65.56503	5.421998
15602	Nearshore	3.1	19.8	22.9	22.17899	15.40856	42.75	87.0521	2.256152
15602	Nearshore	2.8	19.7	22.5	22.58065	15.25161	43.75	88.10376	2.007834
15602	Nearshore	2.8	20.3	23.1	21.97659	15.83875	42.25	88.41463	2.025102
15602	Nearshore	3	21.1	24.1	20.94862	16.67984	39.75	88.10021	2.214836
15602	Nearshore	2.4	21.4	23.8	21.25984	16.85039	40.5	90.37162	1.733207
15607	Nearshore	2.8	21.4	24.2	20.84433	16.93931	39.5	88.94431	2.058153
15607	Nearshore	2.7	21.3	24	21.05263	16.81579	40	89.25204	1.972934
15607	Nearshore	2.5	20.2	22.7	22.38034	15.67917	43.25	89.47951	1.781521
15607	Nearshore	2.9	23.4	26.3	18.58887	19.0502	34.25	89.46664	2.208403
15607	Nearshore	3	22.3	25.3	19.67871	17.91165	36.75	88.66799	2.255334
15736	Wadi	4.3	12.4	16.7	27.97119	8.931573	58.25	75.2199	3.048134
15736	Wadi	4.2	12.3	16.5	28.14371	8.838323	58.75	75.50645	2.96074
15736	Wadi	4.1	12.5	16.6	28.05755	8.992806	58.5	76.24276	2.880371
15736	Wadi	4.2	12.4	16.6	28.05755	8.920863	58.5	75.65589	2.96284
15736	Wadi	4.8	12.6	17.4	27.36077	9.152542	56.5	73.42657	3.490235
15751	Wadi	5.2	11.8	17	27.71084	8.53012	57.5	70.48984	3.835095
15751	Wadi	5.1	12	17.1	27.62364	8.685163	57.25	71.23776	3.747582
15751	Wadi	4.9	11.5	16.4	28.22967	8.253589	59	71.18539	3.556255

15751	Wadi	5	10.7	15.7	28.82562	7.615658	60.75	69.25566	3.633571
15751	Wadi	4.8	10.9	15.7	28.82562	7.758007	60.75	70.50453	3.456855
15763	Wadi	5.6	10.2	15.8	28.74109	7.268409	60.5	65.72165	4.184674
15763	Wadi	5.9	10	15.9	28.65636	7.134364	60.25	64.08202	4.472
15763	Wadi	6	10.2	16.2	28.40095	7.303103	59.5	64.15094	4.571396
15763	Wadi	5.7	10.3	16	28.57143	7.357143	60	65.54248	4.281128
15763	Wadi	5.7	10.2	15.9	28.65636	7.277051	60.25	65.32181	4.280185
15764	Wadi	5.7	10.1	15.8	28.74109	7.19715	60.5	65.09829	4.279334
15764	Wadi	5.6	10	15.6	28.90995	7.109005	61	65.27415	4.183033
15764	Wadi	5.7	9.8	15.5	28.99408	6.95858	61.25	64.41012	4.277349
15764	Wadi	5.9	12	17.9	26.91839	8.769793	55.25	68.16245	4.503389
15764	Wadi	6.1	11.5	17.6	27.18447	8.373786	56	66.49321	4.688946
15781	Nearshore	2.8	23.6	26.4	18.47826	19.23913	34	89.87053	2.129755
15781	Nearshore	1.8	22.7	24.5	20.5298	18.03974	38.75	92.99467	1.291761
15781	Nearshore	2.6	23.9	26.5	18.36735	19.5102	33.75	90.6333	1.969946
15781	Nearshore	2.3	24.1	26.4	18.47826	19.64674	34	91.68727	1.725596
15781	Nearshore	2.2	23.3	25.5	19.46309	18.7651	36.25	91.76841	1.622199
15801	Nearshore	2.5	24.2	26.7	18.14461	19.809	33.25	91.06303	1.895188
15801	Nearshore	2.6	24	26.6	18.25613	19.61853	33.5	90.66868	1.973155
15801	Nearshore	2.6	24.5	27.1	17.69547	20.16461	32.25	90.84168	1.989415
15801	Nearshore	2.5	22.9	25.4	19.57105	18.41823	36.5	90.60336	1.85593
15801	Nearshore	2.1	23.9	26	18.91892	19.37838	35	92.29581	1.556757
15827	Nearshore	1.6	24.8	26.4	18.47826	20.21739	34	94.22492	1.177987
15827	Nearshore	1.2	24.8	26	18.91892	20.10811	35	95.60524	0.868274
15827	Nearshore	1.5	25.3	26.8	18.03279	20.7377	33	94.66791	1.10891
15827	Nearshore	1.4	24.3	25.7	19.2463	19.62315	35.75	94.81077	1.013312
15827	Nearshore	1.4	24	25.4	19.57105	19.30295	36.5	94.74931	1.008287
15849	Nearshore	2	27.1	29.1	15.37377	22.93371	27.25	93.44828	1.558867
15849	Nearshore	1.9	26.2	28.1	16.55076	21.8637	29.75	93.55472	1.451437
15849	Nearshore	2.3	27.8	30.1	14.16309	23.86266	24.75	92.71302	1.839073
15849	Nearshore	2.5	27.4	29.9	14.40799	23.45221	25.25	92.02351	2.002026
15849	Nearshore	2.4	28.1	30.5	13.66906	24.25899	23.75	92.49506	1.937905
15863	Nearshore	1.8	27.9	29.7	14.65149	23.81223	25.75	94.22492	1.410936
15863	Nearshore	1.8	28.3	30.1	14.16309	24.29185	24.75	94.3019	1.421218
15863	Nearshore	1.9	28.1	30	14.28571	24.08571	25	93.96422	1.501214
15863	Nearshore	2	28.3	30.3	13.91679	24.36155	24.25	93.70861	1.592882
15863	Nearshore	2.1	27.2	29.3	15.13437	23.08345	26.75	93.16664	1.646844
15877	Nearshore	2.6	29.6	32.2	11.50442	26.19469	19.5	92.2981	2.177589
15877	Nearshore	2.4	27.5	29.9	14.40799	23.5378	25.25	92.34385	1.917027
15877	Nearshore	2.6	31	33.6	9.638554	28.01205	16	92.62026	2.237132
15877	Nearshore	2.6	30.3	32.9	10.58122	27.09389	17.75	92.46262	2.206894
15877	Nearshore	2.5	29.2	31.7	12.15227	25.65154	20.75	92.47823	2.069053
15890	Nearshore	2.9	29.8	32.7	10.84695	26.56761	18.25	91.5374	2.470453

15890	Nearshore	3.1	29.8	32.9	10.58122	26.6468	17.75	91.00626	2.664231
15890	Nearshore	3.1	28.7	31.8	12.02346	25.24927	20.5	90.69363	2.609567
15890	Nearshore	3.3	30.2	33.5	9.774436	27.24812	16.25	90.59547	2.883469
15890	Nearshore	3.2	31.7	34.9	7.834101	29.21659	12.75	91.24928	2.867402
15893	Sand Flat	5.6	15.1	20.7	24.33796	11.42497	48.25	73.94711	4.314426
15893	Sand Flat	5.7	16.7	22.4	22.68041	12.91237	44	75.51436	4.484151
15893	Sand Flat	5.6	13.3	18.9	26.01726	9.839704	52.75	71.42857	4.249553
15893	Sand Flat	5.5	16.1	21.6	23.46939	12.32143	46	75.49824	4.260321
15893	Sand Flat	5.8	15	20.8	24.24242	11.36364	48	73.13506	4.505377
15898	Sand Flat	6.1	15.2	21.3	23.76112	11.58831	46.75	72.39819	4.812692
15898	Sand Flat	6.2	10	16.2	28.40095	7.159905	59.5	62.93266	4.768033
15898	Sand Flat	6.2	14.9	21.1	23.95437	11.3308	47.25	71.66907	4.900447
15898	Sand Flat	6.4	14.1	20.5	24.5283	10.64151	48.75	69.87116	5.070465
15898	Sand Flat	6.4	14.2	20.6	24.43325	10.73048	48.5	70.01972	5.074543
15900	Sand Flat	6.6	14.2	20.8	24.24242	10.75758	48	69.36981	5.281276
15900	Sand Flat	6.6	14.6	21.2	23.85787	11.11675	47	69.95688	5.298784
15900	Sand Flat	6.7	13.2	19.9	25.09363	9.88764	50.25	67.46742	5.346424
15900	Sand Flat	6.8	13.5	20.3	24.71769	10.16311	49.25	67.63527	5.462494
15900	Sand Flat	6.8	14.1	20.9	24.14665	10.69532	47.75	68.57977	5.486979
15904	Sand Flat	6.9	13.5	20.4	24.62312	10.17588	49	67.31488	5.568338
15904	Sand Flat	7.2	11.7	18.9	26.01726	8.65598	52.75	63.1068	5.832
15904	Sand Flat	7.3	14.5	21.8	23.27366	11.12532	45.5	67.64637	6.04573
15904	Sand Flat	7	13.4	20.4	24.62312	10.1005	49	66.83292	5.671097
15904	Sand Flat	7.1	13.4	20.5	24.5283	10.11321	48.75	66.51775	5.778571
15908	Wadi	4.8	16.2	21	24.05063	12.3038	47.5	78.03468	3.605372
15908	Wadi	4.7	16.7	21.4	23.66412	12.74809	46.5	78.90385	3.533732
15908	Wadi	4.4	14.2	18.6	26.28993	10.46683	53.5	77.25789	3.180158
15908	Wadi	4.9	15.6	20.5	24.5283	11.77358	48.75	77.01802	3.674044
15908	Wadi	5	16.1	21.1	23.95437	12.24335	47.25	77.21823	3.785922
15911	Sand Flat	8.4	11.6	20	25	8.7	50	59.24413	7.189065
15911	Sand Flat	7.5	11.1	18.6	26.28993	8.181818	53.5	60.90535	6.147271
15911	Sand Flat	7.5	11.2	18.7	26.19926	8.265683	53.25	61.11869	6.149119
15911	Sand Flat	7.8	13.4	21.2	23.85787	10.20305	47	64.39212	6.555056
15911	Sand Flat	7.1	12.1	19.2	25.74257	8.985149	52	64.20801	5.734685
15915	Sand Flat	7.4	12.7	20.1	24.90613	9.536921	49.75	64.36898	6.079578
15915	Sand Flat	7.1	12.7	19.8	25.18703	9.501247	50.5	65.31242	5.753068
15915	Sand Flat	7.3	12.9	20.2	24.81203	9.699248	49.5	65.03655	5.976917
15915	Sand Flat	7	12.1	19.1	25.83436	8.974042	52.25	64.53333	5.627764
15915	Sand Flat	6.8	13.4	20.2	24.81203	10.07519	49.5	67.47231	5.458677
15917	Sand Flat	7.3	12.7	20	25	9.525	50	64.68042	5.969885
15917	Sand Flat	7.4	12.7	20.1	24.90613	9.536921	49.75	64.36898	6.079578
15917	Sand Flat	7.4	12.5	19.9	25.09363	9.363296	50.25	64.0041	6.072836
15917	Sand Flat	7.4	12.4	19.8	25.18703	9.276808	50.5	63.81884	6.069612

15917	Sand Flat	7.5	12.9	20.4	24.62312	9.723618	49	64.41948	6.19735
15959	Sand Flat	7.6	12.5	20.1	24.90613	9.386733	49.75	63.38742	6.294651
15959	Sand Flat	7.7	13.2	20.9	24.14665	10.01264	47.75	64.34316	6.433116
15959	Sand Flat	7.8	10.2	18	26.82927	7.463415	55	57.92164	6.471867
15959	Sand Flat	7.8	13.1	20.9	24.14665	9.936789	47.75	63.87128	6.542456
15959	Sand Flat	7.9	12.5	20.4	24.62312	9.422111	49	62.48438	6.633952
15971	Sand Flat	6.5	12.3	18.8	26.10837	9.08867	53	66.57645	5.111009
15971	Sand Flat	6.1	12.4	18.5	26.38037	9.128834	53.75	68.15059	4.710403
15971	Sand Flat	6.2	12.7	18.9	26.01726	9.395808	52.75	68.3163	4.818667
15971	Sand Flat	6.3	12	18.3	26.56059	8.812729	54.25	66.72227	4.899968
15971	Sand Flat	6.3	12.2	18.5	26.38037	8.981595	53.75	67.08826	4.90508
15980	Sand Flat	6.1	13.5	19.6	25.37313	10.07463	51	69.96631	4.744633
15980	Sand Flat	5.8	12.5	18.3	26.56059	9.179927	54.25	69.40589	4.418849
15980	Sand Flat	6	14.6	20.6	24.43325	11.03275	48.5	71.92118	4.686724
15980	Sand Flat	5.9	15.1	21	24.05063	11.46835	47.5	72.92924	4.608322
15980	Sand Flat	6.2	12.9	19.1	25.83436	9.567367	52.25	68.65354	4.82477
16013	Sand Flat	6.9	13.1	20	25	9.825	50	66.64971	5.553333
16013	Sand Flat	6.8	13	19.8	25.18703	9.725686	50.5	66.8037	5.444194
16013	Sand Flat	6.7	13.4	20.1	24.90613	10.06258	49.75	67.79661	5.353721
16013	Sand Flat	6.9	15	21.9	23.17542	11.52369	45.25	69.58942	5.63544
16013	Sand Flat	7	9.8	16.8	27.88462	7.067308	58	59.57447	5.592195
16017	Sand Flat	7.5	9.8	17.3	27.44861	7.110036	56.75	57.90251	6.134843
16017	Sand Flat	7.9	9.6	17.5	27.27273	6.981818	56.25	56.12394	6.584763
16017	Sand Flat	7.7	11.2	18.9	26.01726	8.286067	52.75	60.49149	6.371983
16017	Sand Flat	7.7	10.4	18.1	26.73993	7.619048	54.75	58.70731	6.360624
16017	Sand Flat	7.9	10.4	18.3	26.56059	7.637699	54.25	58.08433	6.586938
16028	Sand Flat	7.9	10.6	18.5	26.38037	7.803681	53.75	58.54736	6.588969
16028	Sand Flat	7.9	11.7	19.6	25.37313	8.731343	51	60.92163	6.609682
16028	Sand Flat	8	10.1	18.1	26.73993	7.399267	54.75	57.06215	6.699486
16028	Sand Flat	8.1	10.2	18.3	26.56059	7.49082	54.25	56.99916	6.815361
16028	Sand Flat	7.7	10.9	18.6	26.28993	8.034398	53.5	59.84079	6.366752
16037	Sand Flat	7.9	10.2	18.1	26.73993	7.472527	54.75	57.61084	6.585482
16037	Sand Flat	8.2	10	18.2	26.65037	7.334963	54.5	56.21135	6.930865
16037	Sand Flat	8	9.8	17.8	27.0073	7.153285	55.5	56.32184	6.698942
16037	Sand Flat	8.1	9.9	18	26.82927	7.243902	55	56.26598	6.814397
16037	Sand Flat	8.2	11.1	19.3	25.65056	8.252788	51.75	58.76125	6.942607
16051	Sand Flat	8.2	9.8	18	26.82927	7.170732	55	55.71347	6.930741
16051	Sand Flat	8.2	8.9	17.1	27.62364	6.441496	57.25	53.32534	6.938842
16051	Sand Flat	8.3	10.3	18.6	26.28993	7.592138	53.5	56.64009	7.049426
16051	Sand Flat	8.5	9.4	17.9	26.91839	6.869671	55.25	53.79113	7.287309
16051	Sand Flat	8.8	9.9	18.7	26.19926	7.306273	53.25	54.21687	7.647727
16054	Sand Flat	8.6	9.7	18.3	26.56059	7.123623	54.25	54.28092	7.405435
16054	Sand Flat	8.8	10.4	19.2	25.74257	7.722772	52	55.4371	7.649706

16054	Sand Flat	8.9	11	19.9	25.09363	8.2397	50.25	56.54074	7.78035
16054	Sand Flat	8.8	9.1	17.9	26.91839	6.650426	55.25	52.11913	7.654229
16054	Sand Flat	8.5	9.7	18.2	26.65037	7.114914	54.5	54.57103	7.285442
16062	Wadi	5.4	12.1	17.5	27.27273	8.8	56.25	70.22635	4.027556
16062	Wadi	5.1	11.7	16.8	27.88462	8.4375	58	70.71623	3.741301
16062	Wadi	5	11.5	16.5	28.14371	8.263473	58.75	70.76923	3.646462
16062	Wadi	5.2	11.8	17	27.71084	8.53012	57.5	70.48984	3.835095
16062	Wadi	4.9	11.5	16.4	28.22967	8.253589	59	71.18539	3.556255
16071	Wadi	4.1	12.5	16.6	28.05755	8.992806	58.5	76.24276	2.880371
16071	Wadi	4.3	13.4	17.7	27.09599	9.769137	55.75	76.63712	3.071711
16071	Wadi	4.3	13.1	17.4	27.36077	9.515738	56.5	76.22927	3.064222
16071	Wadi	4.5	13	17.5	27.27273	9.454545	56.25	75.25326	3.235007
16071	Wadi	4.7	12.5	17.2	27.53623	9.057971	57	73.68111	3.398874
16084	Wadi	5.5	12.6	18.1	26.73993	9.230769	54.75	70.68724	4.134181
16084	Wadi	5.6	12.9	18.5	26.38037	9.496933	53.75	70.80132	4.237567
16084	Wadi	5.8	13.8	19.6	25.37313	10.29851	51	71.46556	4.45929
16084	Wadi	5.8	13.7	19.5	25.46584	10.21118	51.25	71.31702	4.455814
16084	Wadi	6.1	13.5	19.6	25.37313	10.07463	51	69.96631	4.744633